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ABSTRACT

A method for modeling the structure of large social systems has been developed which is based on the interpersonal communication networks present in the functioning system. Recent developments in techniques and computer software have made possible the analysis of networks of several thousand persons. The new technique provides a method for describing social systems which is based on emergent systems properties, rather than arbitrary, prior expectations. A general overview of the recent advances which have brought about these new techniques of analysis is presented. (Author/WH)

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SOCIAL NETWORK ANALYSIS:
AN OVERVIEW OF RECENT DEVELOPMENTS

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ABSTRACT

One important problem in the description of large social systems is developing methods which can adequately describe the structure of those systems. This paper presents a method for modeling structure which is based upon the communication networks present in the functioning system. Communication networks consist of the regular patterns of interpersonal communication which develop among people within a social system as they use various forms of communication (e.g., face-to-face meetings, telephone calls, memos, etc.) to accomplish the daily activities of the system.

While the analysis of communication networks is certainly not new, recent developments in techniques and computer software have made possible the analysis of networks of several thousand persons. Prior research, limited to small networks because of the enormous amount of work involved in the analysis of network data, was forced to make some rather untenable assumptions, resulting in methodologically and conceptually weak studies. The quantity and quality of the data currently available for describing large social systems is certainly less than optimal. The technique outlined herein provides a method for describing social systems which is based upon emergent systems properties, rather than arbitrary, a priori expectations.

This paper is presented as a general overview of the recent advances which have brought about these new techniques of analysis. Additional recent papers are available from the authors which present more theoretical and technical information, as well as papers which present more practically applied information.

SOCIAL NETWORK ANALYSIS:
AN OVERVIEW OF RECENT DEVELOPMENTS

Communication networks have been described by Pool [28] as the "thread" that holds social systems together. An analysis of these networks can, therefore, provide a characterization of the system's structure. If techniques can be developed which allow descriptions of social systems based upon their communication patterns--patterns which are emergent, *a posteriori* system properties rather than imposed, *a priori* expectations --great improvements in methods of modeling large-scale systems may become possible. This paper describes a method for the analysis of communication networks (herein called the H technique) which may address this consideration. Our discussion is presented as a general overview; more complete theoretical discussions can be found in Richards [30, 31, 32, 33]; a very applied, practical discussion is found in Monge and Lindsey [25].

Conceptual Framework

Several inherent problems exist in the analysis of communication nets. First, the size and complexity of the analytic problem pose a very real barrier to research. With 100 persons, for instance, each of the 100 could talk to 99 others. Thus, 9,900 possible connections exist. With a 5,000-person net nearly 25,000,000 possible links exist; if a full matrix were used to represent these contact patterns, the processing capacity of most present day computers would be exceeded. This difficulty has been overcome by an alternate conceptualization of the problem, which

has allowed the development of a computer program (described later) which can handle over 4,000 persons.

A closely related second problem involves the different research strategies which have been used to handle this complexity. While many different methods of describing (or modeling) communication networks exist, there are few standards, or guidelines, for choosing the better or more appropriate of several methods. For example, Mears [22] has delineated one method of modeling communication structure in large organizations. He proposes but does not support the generalization that since most work is done in small five or six person groups, a large organization can be conceptualized as merely a collection of these smaller groups. To improve the communication and thus improve efficiency we merely examine and modify communication patterns within these small units. Notions such as the "wheel," "comcon," etc. are useful in such modifications. While this method does provide a simplification of sorts, it does so at the expense of throwing away a great deal of information, i.e., communication links to members of other groups. If this method could be legitimately applied, then generalizations from laboratory studies of communication nets could be utilized to improve communication flow in small groups.

Mears' treatment is one example of the many studies of this type which are based upon a paradigm roughly analogous to the mechanistic or reductionistic model of science. It assumes that understanding is possible by taking the process apart, looking at the separate parts, and putting it back together again. The necessity of looking only at the parts stems from the fact that the complexity of the whole, functioning

system is far too great for existing analytic methods. Division into parts is relatively arbitrary, and all the information due to the interaction of the parts is lost. The H method, on the other hand, searches for parts (groups) which result from the application of a set of straightforward, explicit criteria to the particular system being considered. It does this by an examination of the total set of interactions among the elements as they function in the whole, operating system; an examination which is conducted independently of any prior expectations concerning the structure of the system. While there is as yet no accepted "standard" for social network analysis, we may suggest a set of criteria that appear to be useful in real-life situations and sensible in terms of the logical basis upon which they rest.

We suggest first that any such criteria must be applied to an a posteriori description of the system, i.e., the system as it is, rather than an a priori specification, i.e., the system as someone thinks it should be. Secondly, if they are to be "standards," these criteria must be explicit and complete. Perhaps one reason network analysis has remained more at the level of art than science is that previous conceptualizations have been ambiguous, thus requiring subjective decisions to be made during any application. Thirdly, the criteria should be formulated specifically to deal with the problems faced in the study of large, complex systems; forced adaptations of other less suitable methods of analysis will not suffice.

In delineating such criteria a standard strategy is to examine existing literature. Massive amounts of empirical data have been

gathered on communication networks. Two considerations, however, preclude the use of most of this information. The first is that most empirical investigations considered small groups of three, four, or five people. Not only is there no general agreement whether generalization is possible across these three group sizes [10], but even if there were, it is doubtful that these findings could be extended to systems having several hundred members. Five-person groups are simply too small to allow the kinds of things commonly observed in larger systems, e.g., hierarchical organization, to occur.

Secondly, according to Collins and Raven [10], an unfortunate state of affairs is quite prevalent throughout the entire network literature. They say, "It is almost impossible to make a simple generalization about any variable without finding at least one study to contradict the generalization. [10, P. 146]" We contend that one factor contributing to this equivocal state of affairs is an improper conceptualization of non-linear dynamic processes as linear, static cause-and-effect relationships. A shift in analytic perspective may possibly rectify this situation.

In addition to the literature mentioned above, which results mainly from experimental investigations of communication networks[3,4], another area of network research is provided in field/survey studies. The sociogram, developed by Moreno [26], has evolved into a number of techniques for the description of system structure. The major intent of a sociogram is to identify cliques or clusters of people who communicate primarily with each other. Closely related are Flament's [13] "kernels."

Methods for locating the various parts or groups within a communication network may utilize graphic methods [26], matrix algebra [17, 12, 9, 21, 37], or formal graph theory [14, 13, 11].

A more general area of literature which does provide some insight into methods for describing large complex systems is systems theory. The description of systems theory given by Buckley [8] leads us to believe that this field may provide some guidelines in the area of articulating a network. According to Buckley, systems theory contends with:

> wholes and how to deal with them as such; the general analysis of organization--the complex and dynamic relations of parts, especially when the parts are themselves complex and changing and the relationships are non-rigid, symbolically mediated, often circular, and with many degrees of freedom; problems of intimate interchange with an environment, of goal seeking, or continued elaboration and creation of structure, or more or less adaptive evolution; the mechanics of "control" of self-regulation of self-direction [8, P. 2].

The notions of "wholes," "parts," and "structure," are, then, considered of primary importance by Buckley. Von Bertalanffy [7] defines general systems theory as "a science of 'wholeness' [7, P. 37]" which deals with "organized wholes." Similarly, Rapaport [29] cites as one element of four constituents of a system definition, "A structure, i.e., recognizable relationships among the elements which are not reducible to mere accidental aggregation of elements [23, P. 21]."

Systems theory has not presented a "new" concept in insisting that analysis proceed from emergent system properties; rather, systems theory has revived and revitalized an important concept which became apparent around the turn of the century. For example, discussions of the necessity of a "holistic" approach can be found in biology [7, 5, 6, 37], evolution theory [36], psychology [38, 18], personality theory [1], etc. The basic problem is well articulated by Smuts [36]:

> This system process cannot be fully defined unless the structure of the system is known; that is, until its fundamental component parts have been identified. However, these parts are neither unchanging or infinitesimal nor do they interact only in pairs. The unitary analysis of a complex system involves the identification within the whole, not of constant entities but of units of formative process, and even in the ultimate analysis these units have a finite extent both in space and time [36, P. 50].

However, a specification of exactly how one proceeds to find these "units of formative process" has not been adequately established. Indeed, Krippendorf [19] mentions this very problem of how the "parts" of complex systems are to be identified as one of the major issues facing systems theory.

The development of the H technique may then be seen as a complimentary adjunct to systems theory. Systems theory provides some abstract notions of how complex organizations should be handled; the H analysis

provides one very specific method of handling a complex organization which takes into account some of these notions.

Network Analysis: The H Technique

The critical distinguishing feature of the H analysis is the method by which communication groups are formed. In this method no decision is made as to what constitutes a communication group (or clique) until the entire pattern of interrelations between individuals has been considered. Thus, if persons in the network left or were replaced, or if measures were taken at different points in time, different communication groupings would likely emerge.

Due to the fact that division into parts could only take place after descriptive data were obtained, and due to the fact that these groupings or structures would change as the system changed, this method of analysis is considered to more adequately reflect emergent properties of a system than techniques which merely impose a structure before analysis begins. We have seen that systems theory embodies a set of general guidelines for describing emergent properties of systems in discussions of "wholes" or "holism." The technique which employs the emergent principles has been called the "H" technique from this notion of "holistic" [20]. In the emergent or H technique, division into parts has been described as proceeding a posteriori. In other words, an a priori decision of how to divide the system into parts is inappropriate. First, all relationships in the organization must be considered; division may then proceed along lines which are appropriate to that organization. To find the communication groups or cliques within the network, a

consideration must be made of all the persons interacting in order to describe (not prescribe) the structure which is present.

In this context, the analytic techniques presented here are well-suited for their task. The measurement process used is one that focuses on the relationships between individual members of the system. The data obtained describe the entire set of relationships among the members, in the context of the intact, functioning system. The analytic methods used were designed specifically for this kind of data, preserving intact units at multiple levels of analysis.

An exploration of the conceptual basis of the systems approach resulted in a confirmation of several ideas which appeared much earlier in the sociometric literature [37, 16, 26, 21]. For example, the model outlined here is roughly hierarchical, with the system as a whole being composed of groups or cliques, which are made up of sets of individuals working together. Individual people in the system can fill any of several roles in terms of the way they contribute to the overall functioning of the system. They can be isolates, for example, or participants of various types. Participants are either group members or linkers, i.e., liaison agents or bridges [16, 37].

The underlying concept here is one of order or structure, in terms of a differentiation of the whole, into parts having specialized functions [27]. As mentioned earlier, this approach is not new. There have, however, been recent advances in an understanding of the nature of structure [2, 31], the kinds of things leading to the development of structure [24], and the ways in which structure can be studied [32].

Once the relevant systems concepts were clarified, their implications could be examined. These implications were found to be far-reaching indeed--demanding a radical shift in analytic techniques. This is so because the structural problem is basically a topological one, where the information describing the system in terms of components and sub-components is clearly nominal data. This suggested that an analysis method based on a topological model would be better-suited, both conceptually and operationally, than traditional methods based upon distance paradigms (for example, multidimensional scaling techniques like factor analysis), which assume more than nominal data and produce other than topological representations of the system.

The first stage in the computerized version of the H technique, using programs developed especially for this task [25, 34, 35], is a topological process, using many concepts drawn from classical sociogram analysis [16, 37], graph theory [12, 13, 14], matrix theory [9, 12, 21, 37], and set theory. These concepts are drawn together into a heuristic pattern-recognition algorithm, which produces a primarily topological solution [33].

After the structure of the system has been "mapped out," other, more conventional, statistical methods may be used to describe properties of various aspects of the system. We thus have a conventional statistical analysis imposed on a topology.

Topological Structural Analysis

Our present analytic capabilities center around a cluster of specially designed computerized methods. The main computer program is

NEGOPY, a network analysis program capable of efficiently analyzing data descriptive of systems having up to 4,096 members [34]. Since the program was based on an algorithm designed specifically for topological structural analysis of large complex systems, it produces results which are readily used by investigators of large systems, rather than results which must be forced into a topological format by complicated interpretative methods. The efficiency of this program is due to the fitting of the algorithm with the data analyzed, the analytic model, and the goals of the analysis. For this reason, NEGOPY is at least ten times as efficient for this type of analysis as most multidimensional scaling routines. In multidimensional methods, a Euclidian distance paradigm is utilized, and results which are very difficult to interpret are produced.

The goals of the program are two-fold: (1) to produce a topological description of the network under investigation, i.e., a list of the groups in the system and a description of the roles of all the individual members in the system, and (2) to calculate a number of statistics descriptive of several parts of the system at various levels of analysis.

An explicit set of goals was needed in order to develop a computerized method of analysis. This explicitness was especially important for the structural aspects of the problem. The result of the re-conceptualization is the following set of definitions and criteria:

I. Nodes may be of two types--participants and non-participants. Non-participants are either not connected to the rest of the network or are only minimally connected. They include:

A. Isolate type one. These nodes have no links of any kind.

B. Isolate type two. These nodes have one link.

C. Isolated dyad. These nodes have a single link between themselves.

D. Tree node. These nodes have a single link to a participant, and have some number of other isolates attached to them.

II. Participants are nodes that have two or more links to other participant nodes. They make up the bulk of the network in most cases, and allow for the development of structure. They include:

A. Group member. A node with more than some percentage of his linkage with other members of the same group. (This percent is called the alpha-percent or α-percent.)

B. Liaison. These nodes fail to meet the α-criterion with members of any single group, but do meet it for members of groups in general.

C. Type other. These nodes fail to meet the α-criterion for any set of group members.

III. To be called a group, a set of nodes must satisfy these five criteria:

A. There must be at least three members.

B. Each must meet the α-criterion with the other members of this g oup.

C. There must be some path, lying entirely within the group, from each member to each other member. (This is called

the connectiveness criterion.)

D. There may be no single node (or arbitrarily small set of nodes) which, when removed from the group, cause the rest of the group to fail to meet any of the above criteria. (This is called the critical node criterion.)

E. There must be no single link (or subset of links) which, if cut, causes the group to fail to meet any of the above criteria. (This is called the critical link criterion.)

The classification of the members of the system in terms of these specifications is accomplished by a two-stage process. First, an approximate solution is obtained by applying a pattern-recognition algorithm to the results of an iterative operation which treats each relationship (link) between a pair of nodes as a sort of vector. This representation is consistent with the topological model being used, since the vectors have two aspects: direction and magnitude. The "direction" of each vector is operationalized as a nominal variable indicating to whom the link goes, while the "magnitude" is operationalized as the strength of the relationship, i.e., the extent to which the behavior of the involved nodes is constrained or influenced because of the relationship. The result of this process is a tentative description of the system's structure. Because this method is an approximate heuristic method, rather than an exact mathematical method, the solution is only an approximation.

An exact solution is obtained by applying the various criteria described earlier to the tentative solution obtained in the first stage. This allows adjustment to an exact solution to be made. Again, several

heuristic devices are utilized to maximize the efficiency of the algorithm.

Statistical Analysis

Once the structure of the system has been determined, the calculation of any desired statistics is straightforward. In network analysis, as in any other area, there are an infinite number of statistics that could be computed for any given network, depending on the viewpoint of the observer of the system (the analyst) and his objectives. If progress is to be made in the understanding of networks and how they work, however, it is essential that the statistics used in one study be comparable to those used in others. For this reason a set of three types of descriptive statistics is suggested in [32] and briefly described here.

First is a set of parametrics, which are themselves not of direct interest, but which are used as "scale factors," allowing all networks to be described on the same scales in such a way that the values obtained will be absolutely comparable, regardless of the size (n = number of nodes) or linkage (l = number of links) of the system. The parametrics include relevant values for both size and linkage at each of three levels of analysis: the whole system, the group, and the individual node.

Second is a set of completeness metrics, all of which express some observed value in terms of a proportion of the maximum that value could take. Here the appropriate parametrics are used to standardize the calculation by defining the metric in the form $M = f(x)$, where f is defined as $f = g(n,l)$; so that g is a parametric in the appropriate n and l; $f(x)$ is the equation for the particular metric, defined in terms

of the parametric g; x is the set of relevant conditions specific to this particular situation; and M is the final value for the metric. An example of this form of a metric equation, together with a graphic representation of the results, is shown in Figure 1.

Figure 1 about here

Included in the set of completeness metrics are: connectiveness, the extent to which the members of a particular unit are linked to the other members of the same unit; connectedness, the extent to which this element is linked to other member elements of the same unit; integrativeness, the extent to which the units linked to this unit are linked to each other; and certain structural indicators, which refer to the extent to which constraint or differentiation is observed in various subsets of the system.

The third set of metrics all refer to the extent to which units vary in the degree to which they show some property. They are thus called dispersion metrics. There are two types of metrics in this class --the difference being found in the way the desired values are calculated. Those of the first type are all expressed as variances, calculated as mean squared deviations.[1] Those of the second type [cf. 24] are entropy- or uncertainty-measuring metrics, and are calculated as logarithmic information theoretic indices of distributional redundancy,[2] i.e., as indicators of the extent to which an event is predictable, given a description of either all occurrences of events or a set of past

occurrences of events. The information theoretic measures are included in the set of dispersion metrics because they refer to the extent to which relative frequencies of occurrence vary from event to event within the set of all possible events.

The set of dispersion metrics includes: the variance in the number of links each node has; the variance in the entries of a given row or column of the distance matrix for a subset of the network; the variance in row or column means for any distance matrix; the variance in the relative frequencies or strengths of the links to a given node; and so on. Also included are information theoretic measures of the extent to which the source or receiver of a given message is predictable; the extent to which the interactions among a set of nodes are dominated by a subset of these nodes [24], and so on.

Inferential Statistics

The metrics described above are all descriptive statistics, i.e., they are used to describe a system under investigation. In addition to the simple descriptive statistics is a set of statistics used for testing hypotheses of various types. These inferential statistics all make use of a model system of some type; for example, the network predicted by a random (unconstrained) model, or the network predicted by using another observed network as a model. Inferences are made by comparing some aspect of an observed network to the same aspect of a predicted network and testing the difference for significance. If the difference is significant, the model used to generate the predicted values is rejected as providing an explanation of the observed network.

Typically, these tests use either the t-test, for working with summary values, or the F-test, for working with variances. Comparisons that can easily be made by matching an observed network to a random one include tests of the variance in the l_i's (l_i is the number of links with node i) and the amount of constraint or structuring in the observed network.

Comparisons can also be made between a subset of an observed network (treating the subset as a sample) and the whole network (treating it as the population) on any dimension for which there is a value for each individual member.

Conclusion

We have described a method for modeling social systems which we feel tends to capture more emergent systems properties than prior conceptualizations. A needed next step in the development of this research program is to relate the endogenous variables described in this paper to exogenous factors. Thus the empirical utility of the H-technique must be demonstrated. Our preliminary applications, such as analyses of large organizations like banks and military bases, have produced insightful and useful data concerning the functioning of these organizations. At an empirical, real-world level, then, utility seems promising.

The potential uses of network analysis are enormous. For example, in "satellite communication" network strategies may be useful in determining optimal locations for ground stations, i.e., perhaps ground stations should be placed within cliques, in order to minimize the cost

of the more expensive terrestial links. Network analysis strategies may further refine notions of knowledge structures in society, and may eventually lead to more efficient human resource information retrieval. More scientific and precise descriptions of "invisible colleges" and related invisible institutions may be described and discussed. Thus with the refinement of these techniques we may be on the verge of an important scientific advance, i.e., new insights into the way organizations work may be possible.

Describing correspondences he has received, Senator Mondale notes the response from a prominent social scientist:

> The behavioral sciences, in my judgment, are in no real position at this point to give any hard data on social problems or conditions. There are many promises and pretensions; however, when it comes to delivery, what is usually forthcoming are more requests for further research . . . [15, Pp. 114-115].

It is our belief that this impotence has resulted partially from a misconception of social systems, and it is our contention that the techniques described herein may vastly improve methods for describing and analyzing such systems.

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Notes

1. i.e., as $S_x^2 = \frac{\Sigma(X_i - \bar{X})}{N}$.

2. i.e., as $H = -\Sigma p_i \log_2 p_i$ for absolute uncertainty, or as

$$H_{rel} = \frac{-\Sigma p_i \log_2 p_i}{\log_2 N}$$

for relative uncertainty.

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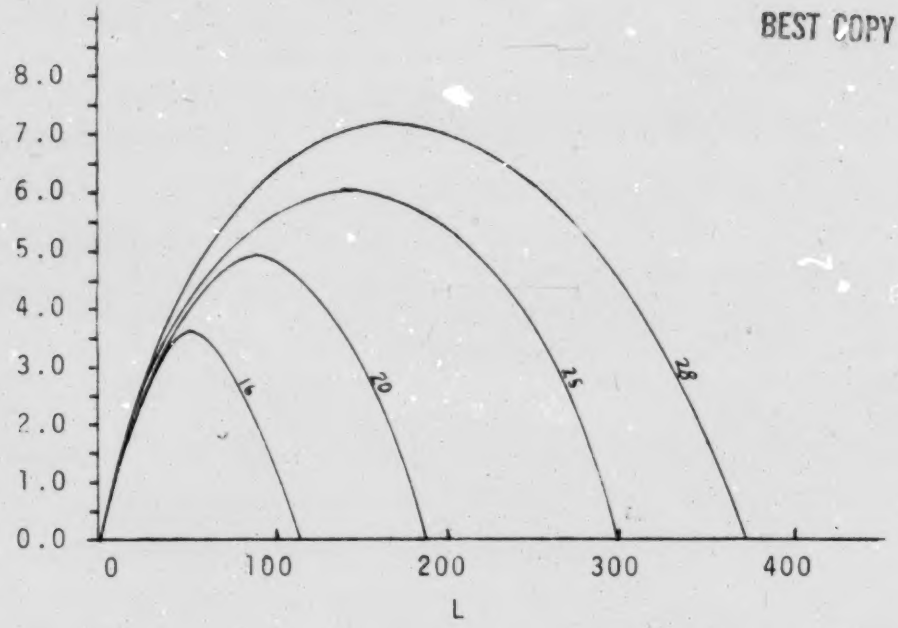

Figure 1a. Plot of expected variance against number of links for Ns (number of nodes) of 16, 20, 25, and 28. Note that each network requires a new graph.

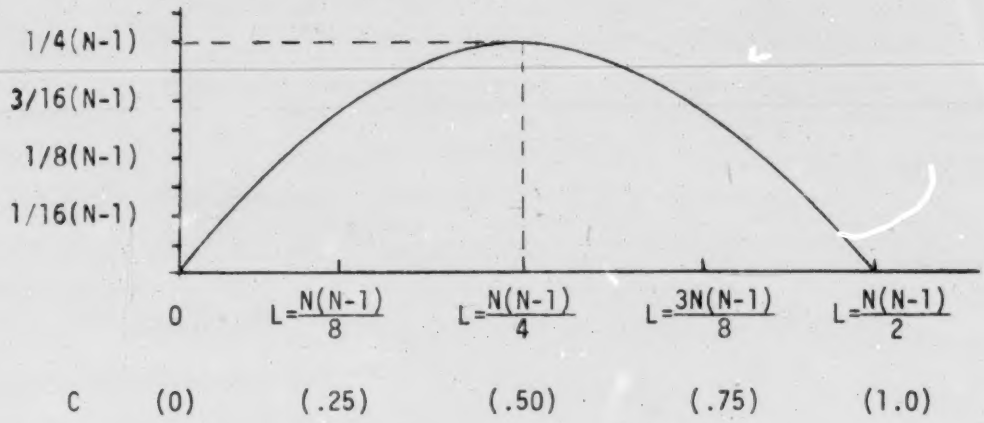

Figure 1b. Generalized plot of expected variance against N and $C^S/_n$ (system connectiveness with respect to nodes). Note that the maximum value for S_e^2 of 1/4(N-1) is at the point where C=.50. At this point, the observed number of links will be one-half of the maximum possible. Note also that all networks, regardless of size (N) and linkage (C), are described by this single graph. Thus, absolute comparisons between networks are possible with this form of description.

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